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# Introduction to Nuclear Criticality Safety

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3/16/21

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# Agenda

1. Why Criticality Safety?
2. Neutronics
3. The Science
4. The Art

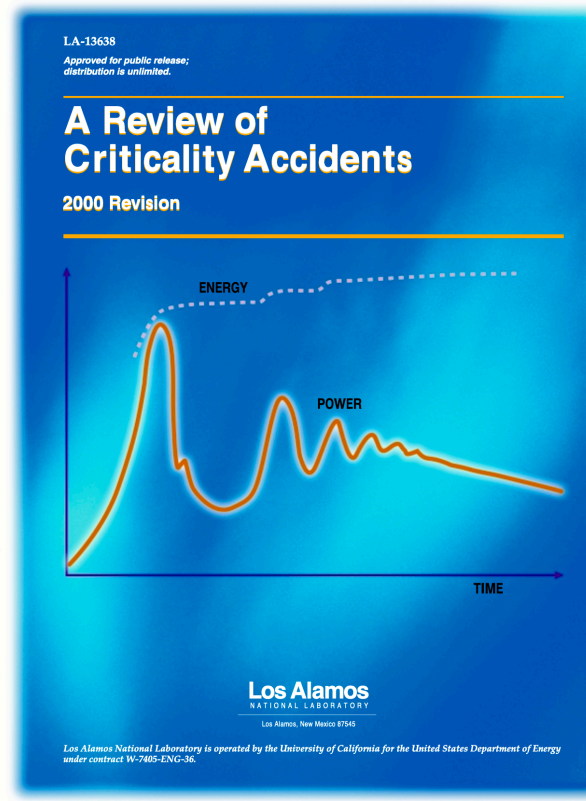




## Why Criticality Safety?



# A Review of Criticality Accidents - LA 13638

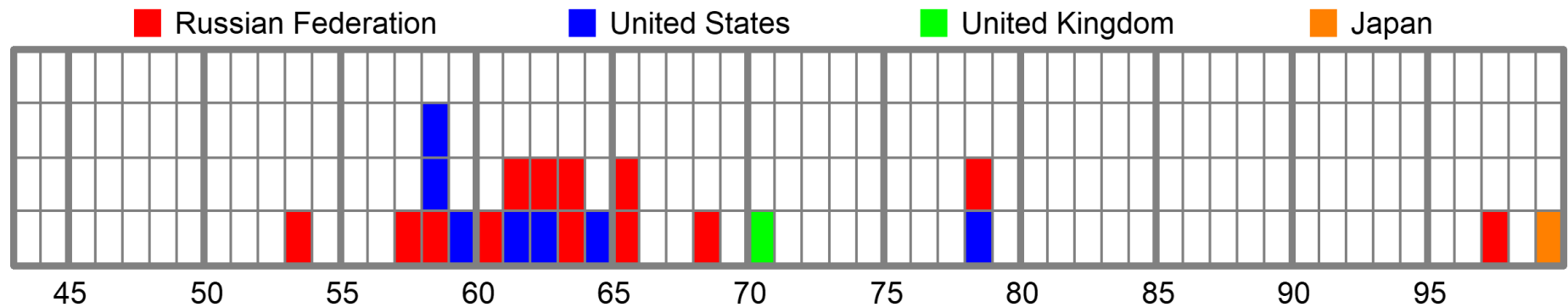


# Historical Accidents

- **Critical Assemblies/Reactor Experiments**
- > 50,000 experiments
  - Designed to determine critical point
- 38 accidents – 12 Deaths
  - Severe damage to the system
  - Severe over exposures to humans
  - Physically unpredicted or equipment malfunction
- **Process Facility Accidents**
- Tens-of-millions of operations since 1943
  - Designed with largest practical safety margins
- 22 accidents
  - 21 involving solution/slurry
    - 4 involving chemistry “gone bad”
  - 1 involving metal ingots

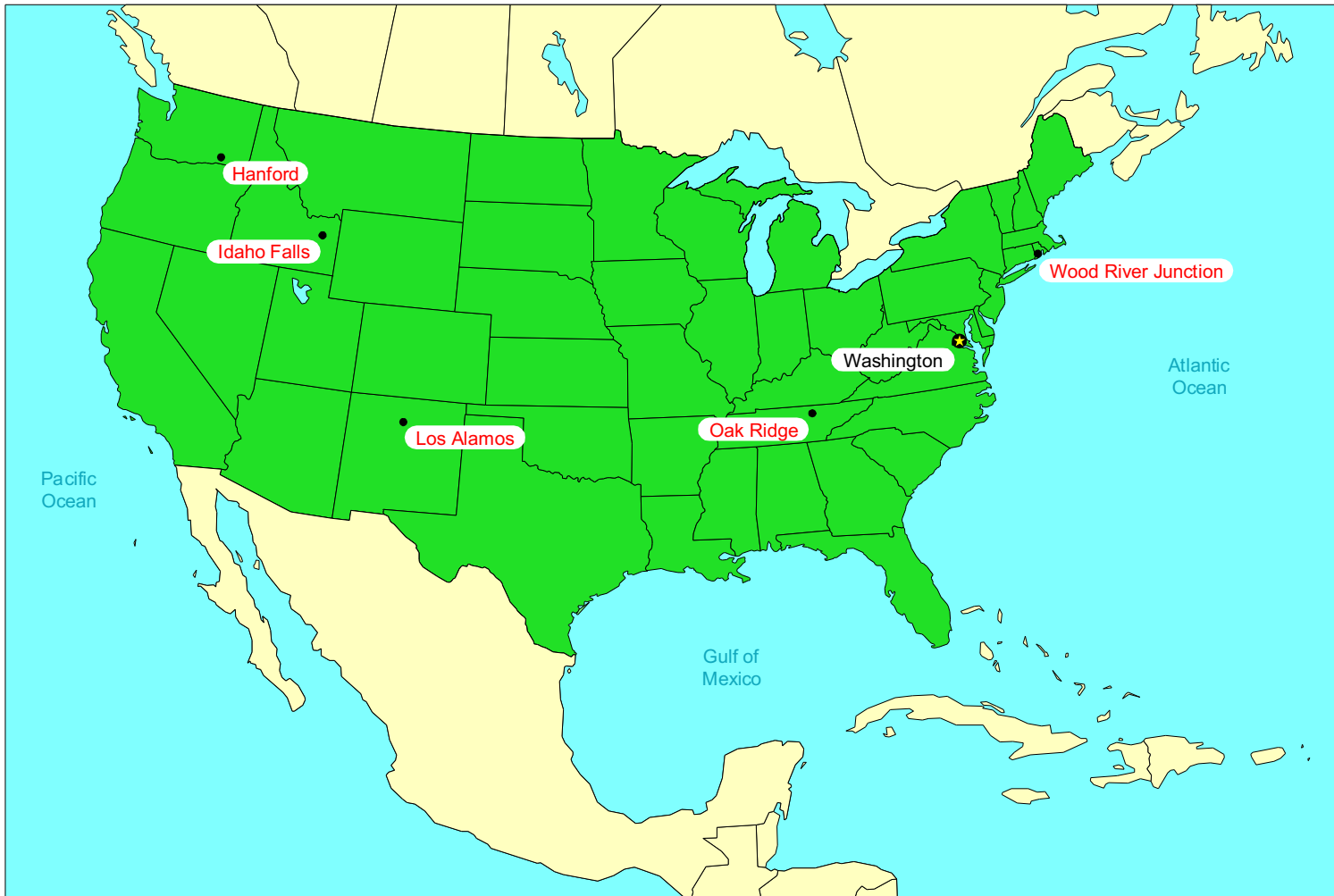


# Historical Frequency



- About one to two process accidents per year for about ten years.
- Then, about one per ten years.





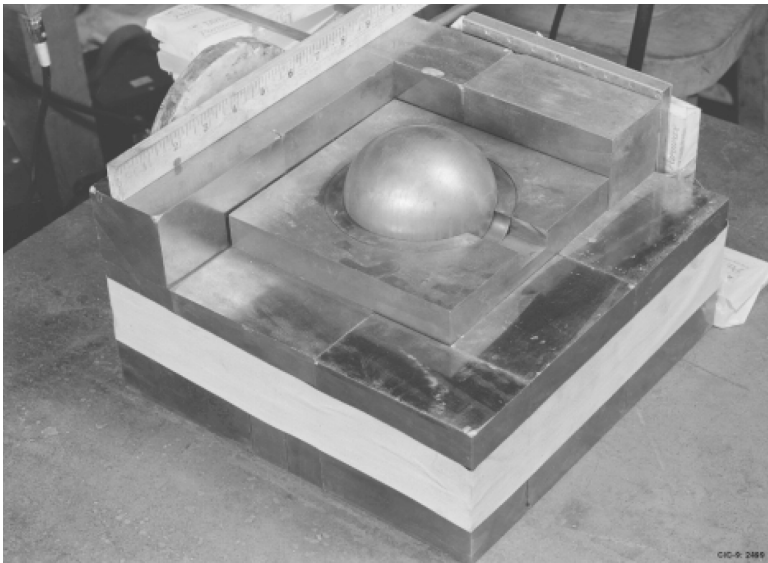


## Harry K. Daghlian, Jr.

- Master's from Purdue in 1944
- Worked in Otto Frisch's criticality group, determining critical masses.
- Experimenting with plutonium sphere
  - Trying to determine amount of tungsten-carbide needed to make Pu sphere go critical
    - ~6 kg  $\delta$ -phase Pu metal
    - Stack tungsten-carbide bricks around Pu until clicks from neutron detector nearly continuous and multiplication roughly 100



## 21 August 1945



*Reenactment of the configuration with about half of the tungsten blocks in place.*

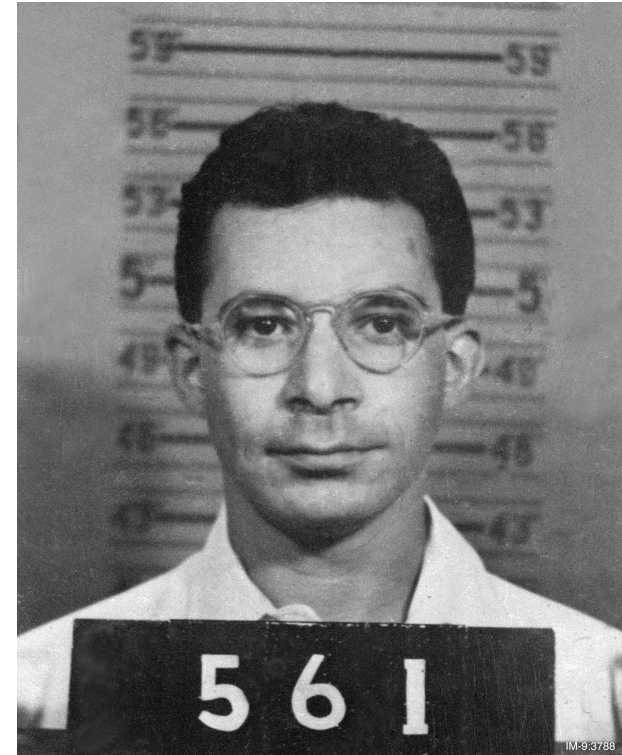
- Working alone, late at night
  - Accident ~9:55pm
- One guard in the room
- Daghlia was moving final brick over assembly
- Neutron counter alerted him assembly would be super critical with addition of final brick
- Withdrew hand, brick slipped and fell on top of the assembly
- System went super critical
- Passed away 28 days later





# Louis Slotin

- Canadian Physicist (PhD)
- Part of team that assembled the Gadget at Trinity
- Arguably most experienced criticality person in the world
- Experimenting with same Pu sphere as Daghlia
  - Trying to determine how much beryllium reflector necessary to make it go critical
- Demonstrating experiment for group of people
  - Eight people in the room



*Louis Slotin*



## 21 May 1946



- Spacers not in place between hemishells
    - Spacing being controlled by Slotin with screwdriver
  - Screwdriver slipped, closing reflector
  - System went super critical
  - Room evacuated and doses measured
- 
- Passed away 9 days later



## What IS Nuclear Criticality Safety?

The prevention or termination of inadvertent nuclear chain reactions in nonreactor environments.

The art of avoiding a nuclear excursion.

Criticality Safety is the **art** and **science** of preventing criticality accidents and ensuring that anyone that could be exposed to one makes it home alive at the end of the day.

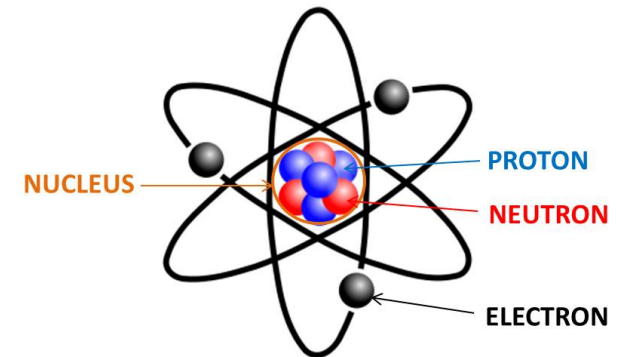


# Neutronics



# What is an atom?

- The structure of an atom is made up of more
- fundamental particles, or subatomic particles:
- Proton: a particle with a positive charge found at
- center of the atom
- Neutron: a particle with no charge found at the center of the
- atom
- Electron: a light and very small particle with a negative charge found in the region far from the nucleus
- **Isotope: Variant of a particular chemical element which differ in neutron number. All isotopes of a given element have the same number of protons but different numbers of neutrons in each atom.**
- **Fission: A process in which the nucleus of an atom splits into two or more smaller, lighter nuclei.**



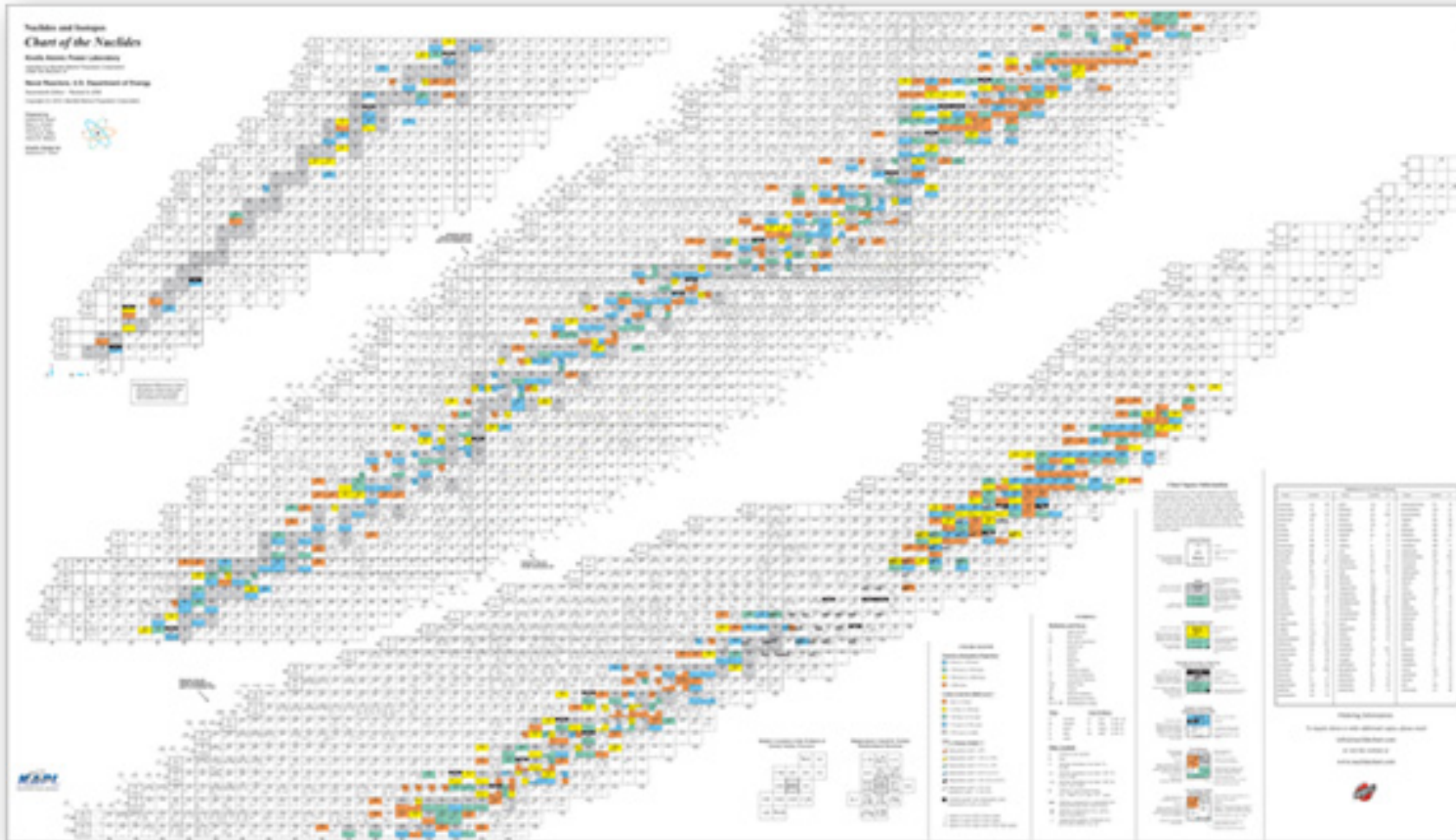
# The Periodic Table of Elements

The Periodic Table of Elements																	
1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57–71 La–Lu Lanthanides	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89–103 Ac–Lr Actinides	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson
		57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	
		89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium	





# Chart of the Nuclides - Isotopes



## The Science



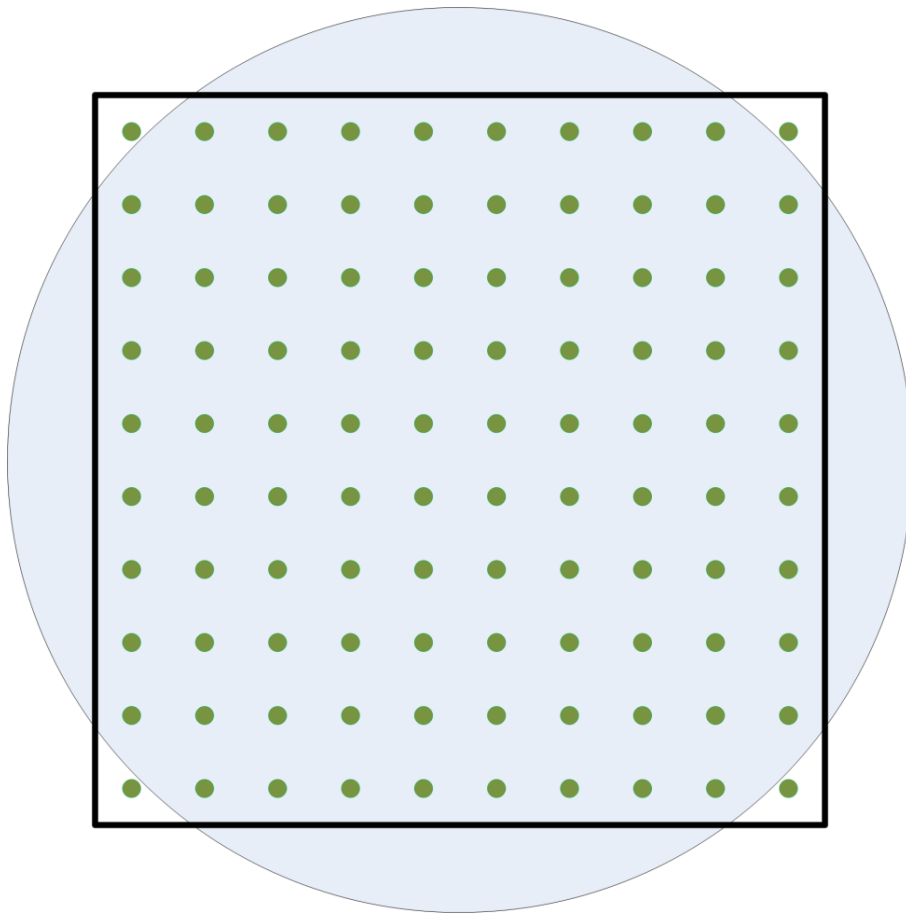


# Criticality Safety Parameters

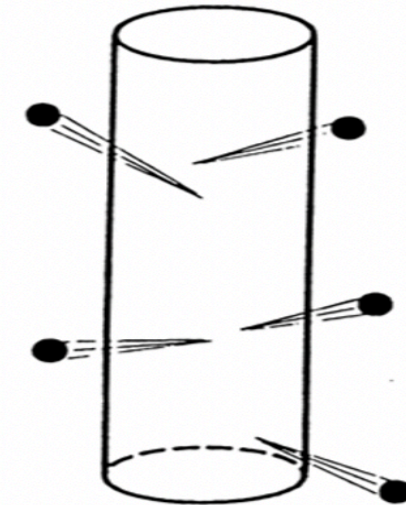
- **M**ass
- **A**bsorption (Neutron Poisons)
- **G**eometry
- **I**nteraction (Spacing)
- **C**oncentration (Density)
- **M**oderation
- **E**nrichment
- **R**eflection
- **V**olume



## Geometry (Shape)



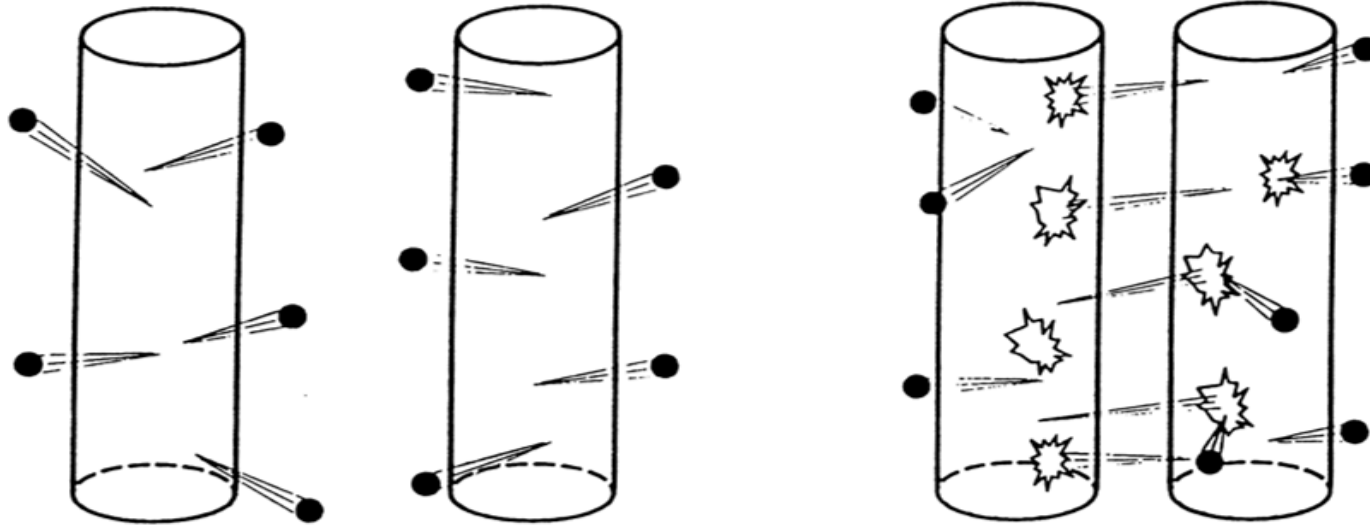
- Equivalent volumes
  - Cube surface area is 600 units
  - Sphere surface area is 483.6 units
  - Sphere has 19% less surface area for the same enclosed material
  - Leakage is higher in cube



Leakage



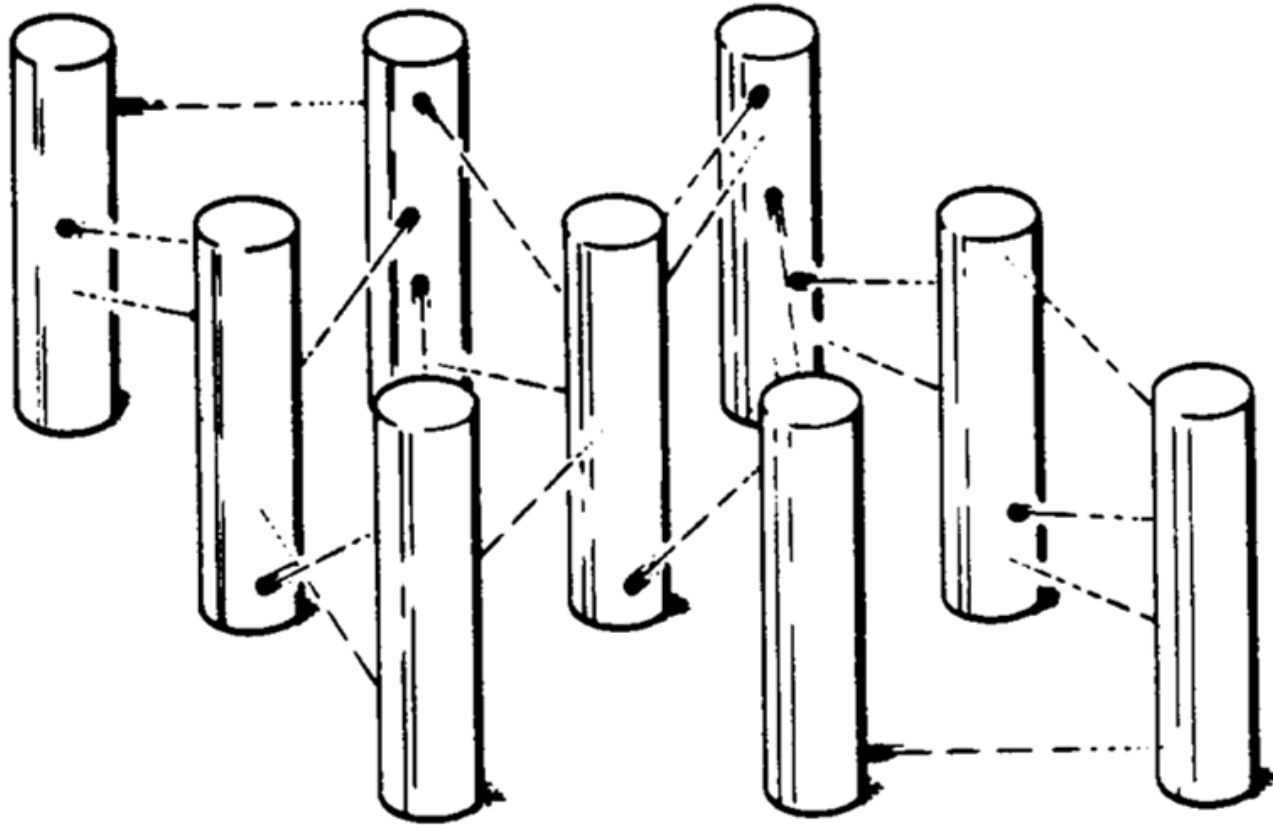
## Interaction (Spacing)



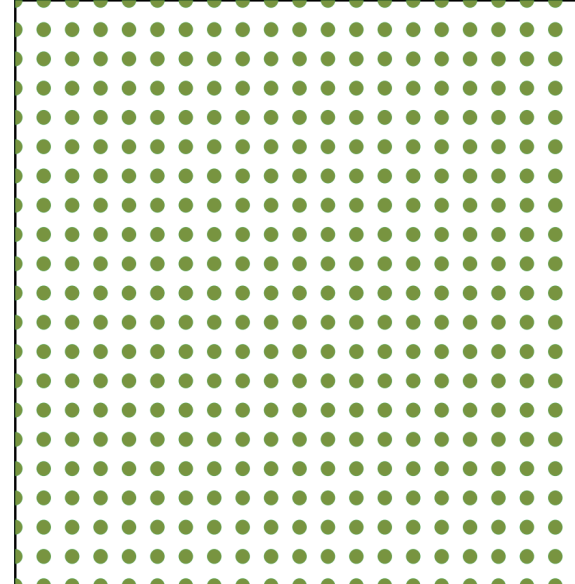
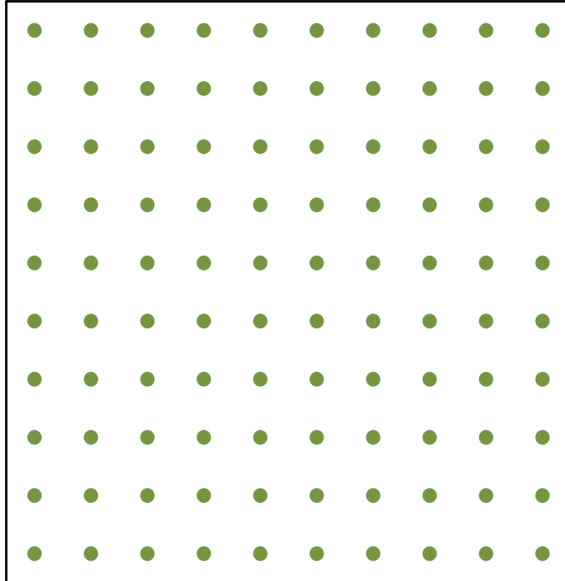
- When two containers are widely separated, few neutrons escaping from one will hit the other
- When two containers are placed close to each other, neutrons escaping from one will be more likely to hit the other



## Interaction (Spacing)



## Concentration (Density)

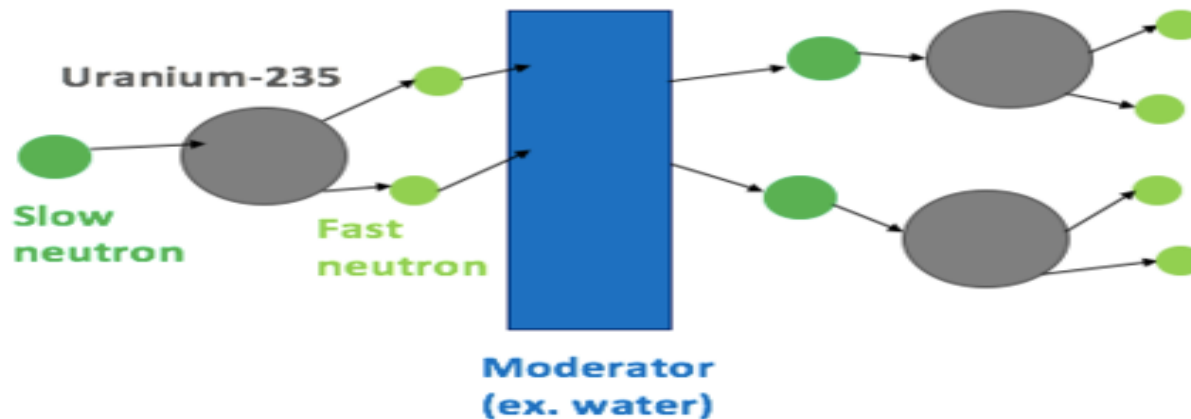


- **Concentration of Number of Fissionable Atoms in Equal Volumes**
- Usually in reference to fissionable solution
- More atoms for neutrons to interact with and cause fission.



# Moderation (Macro System Property)

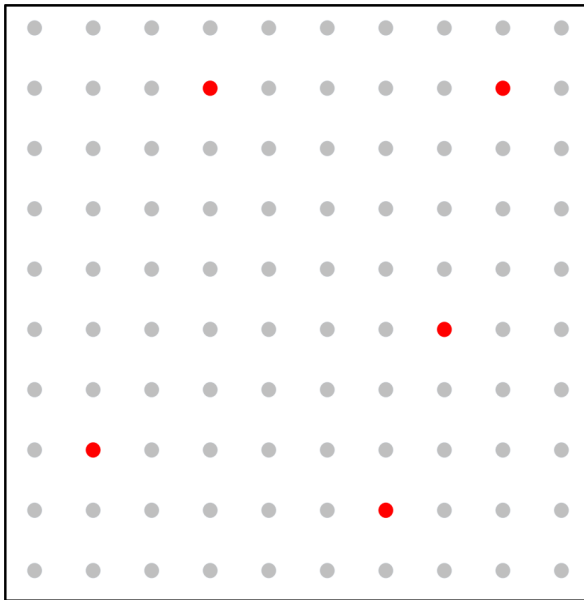
- Neutrons are born with 'fast' energy
- Neutrons are more likely to fission with 'slow' energy
- Moderating material 'slows' neutrons down
- More slow neutrons means more fissionable material absorption
  - More absorption means more fissions
  - More fissions makes a self-sustaining chain reaction easier
- **Water, Graphite, Beryllium, Hydrocarbons (oils) etc.**



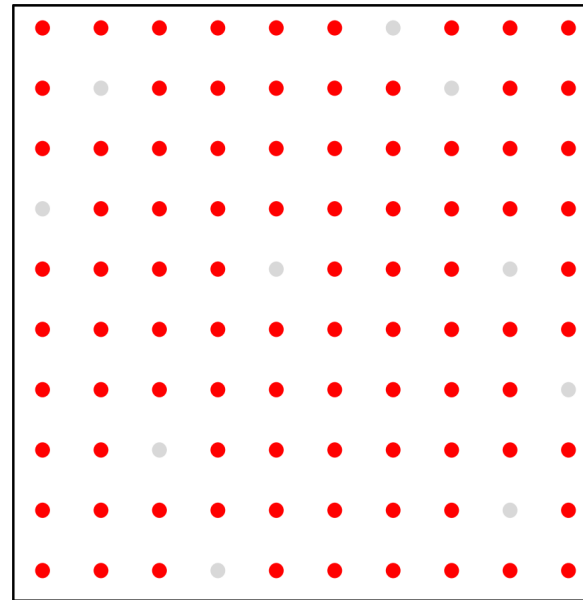
## Enrichment (Fissionable Isotope ratio)

- Uranium from natural sources is **enriched** ( $^{235}\text{U}$ ) by isotope separation, and plutonium ( $\text{Pu}(0)$ ) is **produced** in a suitable nuclear reactor

5%  $^{235}\text{U}$



90%  $^{235}\text{U}$

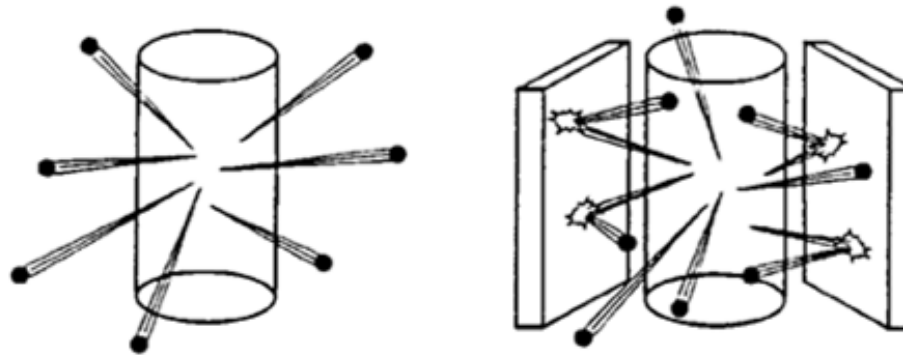


[Enrichment Simulation](https://phet.colorado.edu/en/simulation/legacy/nuclear-fission)

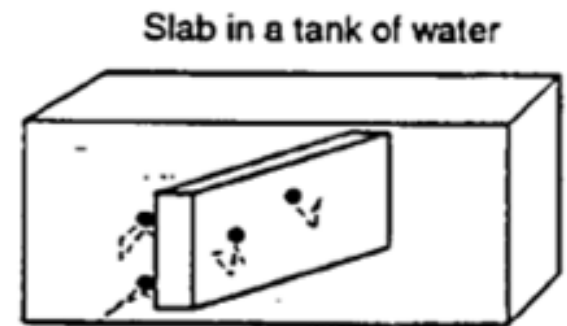
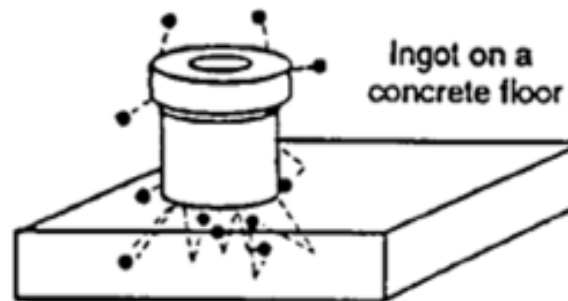
<https://phet.colorado.edu/en/simulation/legacy/nuclear-fission>



# Reflection



- Certain material reflect neutrons reflects neutrons.
- The material may be **water**, **graphite**, **beryllium**, steel, tungsten carbide or other high Z materials.





Questions?



## Homework

- Name 9 Criticality Safety Parameters (MAGIC MERV) and describe how they are controlled.
- Read about the following accidents found in LA-13638 and be prepared to discuss.
  - Idaho Chemical Reprocessing – 17 October 1978 (Page 18)
  - Los Alamos – 30 December 1958 (Page 47)
  - Siberian Chemical Combine – 13 December 1978 (Page 31)
  - Tokai-Mura – 30 September 1999 (Page 53)
- Think about the following while reading about each accident.
  - Were the conditions / processes routine? What about time of accident?
  - What were the causes of the accident? (Human error, equipment failures etc.)
  - Were procedures being followed? How not?
  - Control of Which MAGIC MERV parameters was lost?

